National water allocation statistics for environmental reporting; 2018

Prepared for Ministry for the Environment

March 2019

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NIWA CLIENT REPORT No: 2019049CH
Report date: March 2019
NIWA Project: MFE18502

Quality Assurance Statement		
	Reviewed by:	Charles Pearson
	Formatting checked by:	Rachel Wright
	Approved for release by:	Scott Larned

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Executive summary

The purpose of this work was to update national level statistics of water allocation for use in environmental reporting. This report describes data sources, methods and results of analysis of national environmental indicators for water allocation carried out in 2018. Data used in this analysis were sourced directly from regional council web servers (except for one council whose data were sourced directly). Automated routines were used to consistently:

- download and collate water resource consent data from regional council web services;
- select consents that were active on the analysis date of 14/02/2018;
- predict consented maximum instantaneous rates and maximum annual volumes in rare cases where they were missing;
- locate surface water takes onto segments of the national river network;
- associate groundwater takes with nearby segments of the national river network; and
- calculate downstream effects by accumulating consented takes resulting from non-hydropower, hydropower and their combination down the river network.

Results are displayed in the following ways:

- tables showing summary statistics of consented maximum instantaneous rate and maximum annual volume by use, by source, and by region allowing a national-scale and regional-scale comparison of the number and size of consents between uses and sources;
- maps of accumulated consented rates upstream of each river segment, allowing potential changes to river flows to be visualised; and
- an interactive app allowing interactive inspection of all consents and their potential impacts on river flows across all regions and catchments.

These results can be used to quantify patterns in water allocation. Results showed that surface water consents are distributed around the country whereas groundwater consents are concentrated in zones where aquifers are present and groundwater demand is high. Results also indicated that irrigation has by far the greatest potential to cause widespread alteration to river flows. Hydro-electric power generation schemes have the potential to deplete flows in some locations and augment flows in other locations.

The present study provides the best possible representation of water allocation across New Zealand. It was not designed to be directly comparable with previous studies of water allocation. National environmental indicators for water allocation were previously calculated in 2016. Improved data transfer protocols were developed in the present study resulting in more consent data being available in comparison to that in 2016. Many of the consents that appeared in the present analysis but not in the 2016 analysis had commencement dates prior to 2016. This indicates that an increase in calculated consented maximum instantaneous rate and maximum annual volume between 2016 and 2018 was caused by increases in data availability rather than real increases in consented abstractions.

1 Introduction

1.1 Background

Quantifying pressures on river flows is important because river flow is a vital component for the provision of life supporting capacity in aquatic ecosystems. Methods for calculating national level statistics of water allocation have previously been developed for the Ministry for the Environment (MfE) by Booker et al. (2016). The methods developed by Booker et al. (2016) used water resource consent data to:

- calculate total consented water allocation for surface water takes, groundwater takes and their combination at the national scale, and for each region of New Zealand;
- calculate total consented water allocation for various water uses (e.g., irrigation, industrial) at the national scale, and for each region of New Zealand; and
- map potential pressure of consented abstractions on rivers flows across New Zealand.

These metrics of water allocation and potential pressure on river flows were subsequently used in national environmental reporting (Ministry for the Environment & Statistics NZ, 2017). Further details of the methods, their advantages and disadvantages, the scales at which they can be applied, and how they relate to the National Policy Statement for Freshwater (NPS-FM; MfE, 2015) were subsequently documented in Booker (2018). This work provided quantitative and spatial information to answer the questions: what activities cause pressures on river flows; are pressures on river flows mainly from abstraction of groundwater or surface water; and where in the country are these pressures most concentrated? Booker et al. (2016) provided transparent, defensible and nationally consistent methods for calculating potential pressure of water resource consents on river flows. In the methods applied by Booker et al. (2016), downloading of the required data and their subsequent analysis required several manual steps. Maps were produced from these previous studies. All raw consent and processed data are currently available from the MfE data portal.

- Publicly available consent data are available from https://data.mfe.govt.nz/table/53613-primary-use-and-source-of-consented-freshwater-takes-201314/data/
- Accumulated consented use are available from https://data.mfe.govt.nz/table/53614-accumulated-freshwater-takes-201314/data/

1.2 Aims of this report

The aim of this work is to provide the Ministry for the Environment (MfE) with updated supporting information in relation to national indicators (hereafter referred to as indicators) on water allocation and impacts on river flows. It is important that indicators are calculated using transparent, defensible and nationally consistent methods. It is also desirable to obtain the required data and apply the subsequent analysis in a consistent and efficient manner. Tools that allow inspection of the data and enhance their interpretation are also desirable. The objectives of this report and its associated outputs were:

1. to document the sources of raw data used to calculate indicators;

2. to document any post-processing of these data;
3. to apply the methods developed by Booker et al. (2016) to calculate indicators across the New Zealand national digital river network;
4. to investigate the possibility of automating the collation of water resource consent data and their subsequent analysis;
5. to provide non-spatial indicators for a specified reporting period (e.g., the 2017-2018 hydrological year);
6. to provide spatial indicators for a specified reporting period (e.g., the 2017-2018 hydrological year) and demonstrate how these might be communicated interactively;
7. to provide a written summary of the results for each indicator; and
8. to provide an interactive app that allowed detailed inspection of the input data and calculated indicators.

1.3 Spatial framework

The River Environment Classification (REC; Snelder & Biggs, 2002) is a deductive (i.e., *a priori* defined) natural flow regime classification of New Zealand's rivers mapped onto a digital representation of the river network. Here we used version 2 of the digital national river network because it represents the most up-to-date and accurate representation of New Zealand's river network. This river network comprises 590,000 segments. We note that this is an updated version of the digital national river network compared to that used previously by Booker et al. (2016) to calculate water allocation spatial indicators.

Each segment of the digital national river network is associated with a suite of attributes. These attributes include those that pertain to local conditions (e.g., altitude), attributes that pertain to the upstream catchment (e.g., upstream catchment area), and attributes that describe inter-connectivity (upstream and downstream connections). These attributes are often available for all segments within the network. This has allowed the river network to provide a basis for various national-level analyses of hydrology (Booker & Woods 2014), geomorphology (Booker 2010), invertebrates (Booker et al. 2014) and fish (Crow et al. 2012). The nationwide nature of these data allows methods to be applied consistently, and for results to be reported at national, regional or catchment levels. New Zealand's national river network, as defined in the REC (version 2) was therefore used as the spatial framework for all analysis in this project.

2 Input data

2.1 Water resource consent data

In New Zealand, regional councils and unitary authorities are responsible for various aspects of managing freshwater resources. They administer consents to take and use water and they hold records of water use and observed river flows. They also delineate management units and set planning provisions in regional plans. These agencies therefore hold a great deal of information that is critical for the calculation of indicators. The data used to calculate indicators in this work were obtained from two sources. These were: a) by remotely accessing data from council servers; and b) by requesting specified data from one council (Otago Regional Council) directly. These data included various information types and required some post-processing (Table 2-1). All remotely accessed data were downloaded 18/07/2018. To the best of our knowledge, the date that the data were upload by each regional council was not available. We assumed that the accessed data were fit for purpose in relation to a national analysis of consumptive water use. Consents whose primary source was missing were designated to be surface water consents. This designation applied an environmentally conservative method because it assumed a "worst-case scenario" from the prospective of impacts on streamflow.

Table 2-1: Obtained variables.

Variable	Description	Post-processing
Maximum annual volume (maxannual)	The maximum volume of water that can be abstracted in a year in cubic metres per year.	Should not exceed volume obtained by constantly exercising maximum instantaneous rate.
Maximum instantaneous rate (maxrate)	The maximum rate at which abstraction may occur in litres per second.	Should not exceed maximum annual volume if exercised constantly for less than one week.
Primary Use	The primary purpose for which the water is being used (e.g., irrigation, industrial, drinking, hydro, mixed etc.).	All uses that were concatenations of various uses were labelled as being in the "Combined / Mixed" category.
Primary Source	The primary source from which the water has been abstracted (groundwater or surface water).	All sources that were not labelled as Groundwater (Not Specified, Storage, Stream Depleting) were assumed to be Surface Water.
Co-ordinates	Latitude and Longitude.	Transformation from NZTM to WSG84 grid system where necessary.
Commencement date	Date on which the consent was granted.	NA
Expiry date	Date on which the consent is due to expire.	NA
Consent status	An indication of whether the consent status (e.g., surrendered, granted, expired, current, active)	NA Note; only available for: Southland, Hawke's Bay, Gisborne.

A primary use of each consent was supplied for most of the consents. Many descriptive categories of primary use were contained within the dataset. We translated the supplied primary use into a smaller number of categories using the mapping shown in Table 2-2.

Table 2-2: Mapping of raw primary use categories to those used in analysis.

Primary use used for analysis	Raw primary use
Drinking	"Communal Scheme", "Domestic", "Domestic Communal", "Domestic, Ancillary Use", "Drinking", "Municipal", "Water Supply Domestic", "Water Supply Domestic Communal", "Water Supply Rural Scheme", "Water Supply Town Supply", "Water Suppy Rural Scheme"
Hydroelectric	"Electricity Generation", "Electricity Generation, Irrigation", "Hydro", "Power Generation"
Industrial	"Aquaculture", "Commercial", "Commercial /Industrial", "Commercial/Industrial", "Construction/RepairsSite", "Industrial", "Mining"
Irrigation	"Irrigation", "Winery"
Mixed/Other	"Amenity/EnvironmentEnhancement", "Amenity/Environment Enhancement" , "Ancillary Use", "Ancillary Use, Vineyard Spraying, Irrigation", "Combined / Mixed", "Domestic, Industrial", "Domestic, Irrigation", "Domestic, Irrigation, Industrial", "Domestic, Winery", "Flood Prevention", "Frost protection", "Frost Protection", "Frost Protection, Irrigation", "Frost Protection, Irrigation, Stock/Domestic", "Frost Protection, Irrigation, Storage", "Frost Protection, Storage", "Frostfighting", "Gone - no longer an issue", "Irrigation, Ancillary Use", "Irrigation, Ancillary Use, Winery", "Irrigation, Commercial", "Irrigation, Communal Scheme, Storage", "Irrigation, Domestic", "Irrigation, Frost Protection", "Irrigation, Stock Water", "Irrigation, Stock/Domestic", "Irrigation, Stock/Domestic, Storage", "Irrigation, Storage", "Irrigation, Storage, Stock Water", "Irrigation, Vineyard Spraying", "Irrigation, Winery", "Irrigation, Winery, Ancillary Use", "Other", "Recreation/Club Facility", "School/Educational Facility Supply", "Silt Control", "Single Household/Stockwater", "Snowmaking", "Stock/Domestic", "Stock/Domestic, Ancillary Use", "Stock/Domestic, Communal Scheme" , "Storage", "Tourist Facilities", "Vineyard Spraying, Ancillary Use", "Waste/Sewage Treatment", "Not specified", "Not Specified", "Dairy Shed/Stockwater", "Stock"

2.2 Hydropower consents

Pressure on flow regimes resulting from consumptive non-hydropower consents is likely to occur at different temporal scales to that resulting from hydropower operations. This is because demand for irrigation, domestic, and stock purposes are likely to vary seasonally, and be ongoing during the summer months. In contrast, hydropower operations are more likely to occur according to power demands, river flows, lake levels and electricity prices. Consented maximum rates of abstraction granted for hydropower generation may be very high to allow for power generation (and possibly filling of storages in reservoirs) during times of high flow. These maximum rates of abstraction are more likely to be limited by engineering infrastructure issues than environmental issues because they are also often accompanied by residual flow requirements (e.g., requirements to maintain flows downstream of the Opuha dam in Canterbury). We therefore created two separate datasets describing non-hydropower consents (i.e., standard consumptive consents for irrigation, industrial, domestic, and other uses) and hydropower consents.

To create these two separate datasets, we inspected the regional council consent dataset and found several consents describing hydropower schemes. We classified these into consumptive and non-consumptive hydropower. We defined consumptive hydropower schemes as those that depleted river flows for some length of the river network over the long term (i.e., presence of the scheme changed the all-time average flow). This definition captured diversions within the same catchment, inter-catchment diversions, and diversions to the sea. This definition did not capture dams that store water but release that water immediately downstream at a later date. These comprised the non-consumptive hydropower schemes. We removed non-consumptive hydropower consents from the analysis. However, we did identify the locations of 60 pieces of non-consumptive hydropower infrastructure representing in-stream dams. The potential influence of these pieces of non-consumptive hydropower infrastructure on river flows was not included in the analysis of pressure on water resources caused by consumptive abstraction reported below. The non-consumptive hydropower infrastructure pieces were not included in the analysis of consumptive abstraction because they do not alter average river flows. However, in-stream dams do have the potential to alter flow regimes through alterations to low flows, seasonal patterns, and flushing flows (e.g., Lessard et al., 2013). Methods for quantifying hydrological alteration caused by non-consumptive hydropower consents, along with examples are provided by Griffiths and Booker (2019).

We compared the consumptive hydropower consents from the regional council consent database with information describing hydropower schemes supplied by MfE, the Electricity Authority dataset of New Zealand power stations[1], and power scheme lists used in compiling the national water accounts[2]. From these combined sources of information, we compiled relevant data (Table 2-1) describing 235 pieces of consumptive hydropower infrastructure. We compiled maxrate values for all 235 pieces of consumptive hydropower infrastructure. We did not compile any maxannual values for any pieces of consumptive hydropower infrastructure. Many pieces of consumptive hydropower infrastructure were missing from our original regional council consent dataset.

For each piece of consumptive hydropower infrastructure, we used location information to identify segments of the REC river network that the water was sourced from, and segments of the REC river network that the water was directed to. Positive values of take (maxrate) were associated with segments of the REC river network that the water was taken from. Negative values of take were associated with segments of the REC river network that the water was directed to. Negative rates of take represented augmentation of river flows from flow diversions. Rates of take for each piece of consumptive hydropower infrastructure were generally equivalent to their rates of discharge because all taken water was discharged somewhere within the river network. Consequently, rates of take for each piece of consumptive hydropower infrastructure summed to zero except where the scheme discharges to the sea (Manapouri, a small Taranaki scheme and a small consent in Milford Sound).

We removed all consents present in our hydropower dataset from the regional council consent dataset to avoid duplication. We then inspected 35 remaining consents labelled as having

[1] http://www.emi.ea.govt.nz/Datasets/Browse?directory=%2FStationList&parentDirectory=%2FDatasets%2FWholesale%2FArchive%2F201310_Centralised_dataset%2FCentralisedDataset%2FNetworkConfiguration%2FGeneration
[2] http://www.stats.govt.nz/browse_for_stats/environment/environmental-economic-accounts/water-physical-stock-account-1995-2010.aspx

"hydropower" as their primary use within the regional council consent dataset. These 35 consents were for relatively small rates of abstraction. Their highest maxrate was 0.5 m^3s^{-1}. Their mean maxrate was 59 ls^{-1}, and their median maxrate was 10 ls^{-1}. We noticed that several of these consents were located nearby to other consents for much larger maxrates and to hydropower buildings. This suggested that these consents related to water supply to the hydropower buildings rather than for direct hydropower production. We therefore re-labelled primary use for these 35 consents to be for industrial purposes.

3 Methods

3.1 Which consents were included

No consents allow for the indefinite right to abstract or use water. Each consent has a commencement and termination date. To avoid including expired consents in our analysis, we selected a particular "analysis date". This date was 14 February 2018. Results were only reported for consents that were active on this date. We selected this date because it falls near to the likely peak of the irrigation season for the water year (July 2017 to June 2018).

We obtained raw data describing 30,483 consents in total. We aimed to conduct our analysis on consumptive consents active on 14 February 2018. Applying this analysis date resulted in the removal of 10,698 consents. A further 166 consents were removed because they contained no information describing maximum allowable rates of abstraction (i.e., information on maximum instantaneous, daily, weekly, monthly and annual abstraction were all missing or blank). A further 2,800 consents were removed because all maximum allowable rates for each consent were either zero or missing (Table 3-1). A further 64 consents were removed because they were contained within our consumptive hydropower infrastructure data. Finally, 42 consents were removed because they were identified as being non-consumptive, unrelated to freshwater, or as being significant duplicate entries. We defined significant duplicate entries as those with a maximum instantaneous rate greater than 0.5 m^3s^{-1}, and as having the same consent identifier, position, source, use, maximum instantaneous rate and maximum annual volume. Applying this definition meant that 104 consents with the same consent identifier, position, source, use, maximum instantaneous rate and maximum annual volume, but relatively small maximum instantaneous rates were not removed from the analysis. Of these 104 consents 75 did have different expiry and commencement dates; suggesting they were legitimate entries in the consent database. The average maximum instantaneous rate of these 104 consents was 44 ls^{-1}. This implied their inclusion did not have a significant influence on the analysis. A total of 16,713 non-hydropower consents remained after having removed consents for the various reasons described above.

Table 3-1: Number of consents in each region.

Region	Removed because expired	Removed because of zero or blank rates	Removed because hydropower or duplicate	Remaining for further analysis
Northland	15	20	0	471
Auckland	276	16	0	845
Waikato	22	1958	7	766
Bay of Plenty	2	0	0	109
Gisborne	1	1	2	160
Taranaki	6	0	8	183
Manawatu-Wanganui	1131	556	18	988
Hawke's Bay	8600	183	11	2585
Greater Wellington	204	28	0	450
Tasman and Nelson	289	0	0	835
Marlborough	66	46	2	1398
West Coast	5	71	15	154

Region	Removed because expired	Removed because of zero or blank rates	Removed because hydropower or duplicate	Remaining for further analysis
Canterbury	76	1	2	5227
Otago	0	85	37	1680
Southland	5	1	4	862
National	10698	2966	106	16713

3.2 Mapping consents onto the river network

Co-ordinates describing the position of the point of take were supplied for each consent. We applied the same method as Booker et al. (2016) previously used to locate consents onto the river network. A brief description is supplied in the remainder of this section.

This information was used to assign each non-hydropower consent to one (for surface water takes) or many (for groundwater takes) segments of the REC river network using an automated procedure. Each groundwater consent was associated with all segments on the New Zealand river network whose centroid was within a 2000 m radius of the coordinates describing the groundwater take point. This method assumed that a groundwater take would deplete river flows within the specified radius (Figure 3-1).

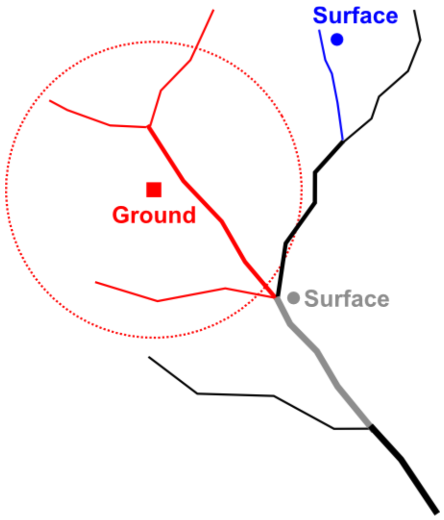

Figure 3-1: A schematic diagram showing the segment assignment for groundwater and surface water takes. The colour of the segment depicts the take it has been assigned to. For groundwater consents, all segments within 2000m were assigned to a given take (red), while surface water consents were assigned to the nearest segment (blue). If more than one segment was within 100m of a surface water consent, the consent was assigned to the segment with the greatest mean annual low flow (MALF) (grey).

Non-hydropower surface water consents were assigned to a single segment on the New Zealand river network by identifying the nearest segment based on the distance to points describing river lines. Where more than one segment had some part of its river line within 100m of the consent location, the segment with the largest estimated seven-day mean annual low flow (MALF) from Booker and Woods (2014) was assigned to the consent (Figure 3-1). This method was used in an attempt to avoid incorrectly associating surface water takes with very small streams, and therefore overestimating the effect of abstraction. All hydropower consents were manually assigned to a segment on the New Zealand river network using the sources of information given in Section 2.

3.3 Proportioning takes between segments

We applied the same method as Booker et al. (2016) previously used to proportioning takes between segments of the river network. A brief description is supplied in the remainder of this section.

We proportioned each groundwater take between its assigned segments as a function of distance and river low flow. The inverse distance squared was used to represent distance from groundwater take to each river segment. The MALF from Booker and Woods (2014) was used to represent river low flows. Assuming T_j is the jth groundwater take, Q_{ij} is river depletion rate at segment i resulting from the jth groundwater take, d_{ij} is distance from the jth groundwater take to the ith segment, and Q_i is the river depletion rate of the ith segment with $Q_i = \sum_j Q_{ij}$. River depletion from each groundwater take was proportional to the MALF of segments multiplying by inverse squared distance as follows:

$$w_{ij} = \frac{MALF_i/d_{ij}^2}{\sum_i (MALF_i/d_{ij}^2)} \quad (1)$$

$$Q_{ij} = \begin{cases} w_{ij}T_j & (d_{ij} < 2km) \\ 0 & otherwise \end{cases} \quad (2)$$

3.4 Rates and volumes

We applied some quality checks to the maxrate and maxannual values within our non-hydropower dataset before applying our analysis. A total of 13,670 consents had a maxrate and a maxannual that were both non-missing and non-zero. Where maxrate and maxannual were both available, we compared these values against each other to apply a check on the supplied numbers. We calculated the time it would take for the maxrate to accrue a volume equal to the maxannual (DaysToMaxannual). We followed the method previously applied by Booker et al. (2016) such that when this time period was less than one week we reduced the maxrate to be the rate that would result in the maxannual being accrued in one week. This was the case for 356 consents (2 per cent of those with values) for which both maxannual and the maxrate were supplied. We applied this method to reduce the influence of a small number of very large maxrate values that could only be exercised for short durations according to their maxannual values.

We identified 60 and 114 consents for which DaysToMaxannual was greater than 1000 and 500 days respectively. We did not amend either maxrate and maxannual for these consents because we were unable to determine whether their maxrates were in error (too low compared to maxannual) or their maxannual were in error (too high compared to maxrate). This method was consistent with that previously applied by Booker et al. (2016).

The dataset included the maxannual and the maxrate for each consent in many cases. However, not all consents contained a non-missing and non-zero maximum annual volume and a maximum instantaneous rate. Of all consents, 5 per cent (802) had a missing maxannual or a maxannual that was zero even though maxrate was not zero. For these "missing maxannuals" we predicted maxannual from maxrate, source, use and region (see Table 2-1 for details). We applied a linear regression (in $\log_{10}$ space) to predict maxannual. This linear model produced an r^2 value of 0.80 (F= 2927 on 19 and 13650 d.f., $p < 0.001$), and all predictors were statistically significant ($p < 0.001$). We then predicted missing maxannual values after having applied an appropriate smearing factor to avoid any potential bias in back-transformation (Duan 1983) using the method described by Costello et al. (2014).

Of all consents, 13 per cent (2241) had a missing maxrate or a maxrate that was zero even though maxannual was not zero. For these “missing maxrates” we predicted maxrate from maxannual, source, use and region. We applied a linear regression (in $\log_{10}$ space) to predict maxrate. This linear model produced an r^2 value of 0.81 ($f = 3121$ on 19 and 13650 d.f. $p < 0.001$), and all predictors were statistically significant ($p < 0.001$). We then predicted missing maxrate values using the method described above when back-transforming.

3.5 Upstream accumulation

After having predicted missing values where possible, all remaining consents were associated with a maxannual and a maxrate. We then calculated the accumulated maximum rate (AccMaxrate) for each segment in the New Zealand river network. After assigning each take (or a proportion of each take in the case of groundwater takes) to a segment, we routed each of these values downstream to calculate the cumulative effects of all upstream consents. This procedure was repeated separately for each category of use (e.g., irrigation consents, industrial consents) and separately for each category of source (e.g., all groundwater consents, all surface water consents). This allowed the cumulative effects of any category of either use or source as well as the total AccMaxrate to be expressed.

Values of AccMaxrate can be expressed as rates in litres per second (or cubic meters per second) to indicate the magnitude of stream depletion regardless of stream size or river flows. However, this magnitude does not take into account the relative size (or flow rate) of the river being depleted. Therefore we also calculated the standardised AccMaxrate by dividing the AccMaxrate by the estimated naturalised median flow, where the median flow is the flow that is exceeded for 50 per cent of the time over the long-term. The standardised AccMaxrate represents the proportion of the median flow that is consented upstream for each segment. For example, for a particular segment, a value of 0.1 indicates that one tenth of the median flow at that segment would be abstracted from upstream if all consents were being exercised at their maximum instantaneous rates. A value of one indicates that the median flow at that segment would be abstracted from upstream if all consents were being exercised at their maximum instantaneous rates. Negative AccMaxrate values indicate that flow augmentation resulting from hydropower diversions exceeds upstream accumulated abstractions.

Naturalised estimates of various hydrological indices were available following the work of Booker and Woods (2014). These represent the best available estimates of flow indices such as the seven day MALF, mean flow and median flow in the absence of major abstractions. See Booker and Woods (2014) for details of how these hydrological indices were calculated and tested. We chose to standardise by the median flow rather than MALF because during low flow abstractions may be restricted and because some rivers can experience extremely low flows for limited periods, but still exhibit large flows at other times.

No data describing restriction of consents (i.e., where abstractions are required to cease or be reduced due to low river flow, low groundwater level, or other specified conditions) were available for this dataset. When accumulating we therefore assumed a worst-case scenario where all consents are unrestricted.

For the reasons stated in Section 2.2, we conducted separate analysis on: a) non-hydropower consumptive consents; and b) hydropower consumptive consents. We first conducted an analysis of all consumptive non-hydropower consents. We then conducted a separate analysis of all consumptive hydropower consents. Finally, we combined these two analyses to describe the potential pressure from both consumptive non-hydropower and consumptive hydropower together. This method allowed the results of these two analyses to be summed to report results for all consents together.

3.6 Displaying the results on paper

Results were displayed using several methods:

- Tables showing summary statistics of consented maxrate and maxannual by use and source. These tables give a national-scale comparison of the number and size of consents between uses and sources.
- Tables showing summary statistics of consented maxrate and maxannual by use and source in each region. These tables give a regional-scale comparison of the number and size of consents between uses and sources.
- Maps of consent locations by use and source. These maps showed the spatial distribution of consented takes. They illustrate in which locations certain uses and types are most concentrated across the country.
- Maps of accumulated consented rates. These maps allow assessment of potential changes to river flows. They represent a worst-case scenario of changes to river flows. These maps can show absolute rates, indicating the amount of water supplied. Alternatively, standardised rates can be shown to indicate the relative effect on stream flows.
- An interactive mapping tool what displays the position of consents, and their potential impacts on downstream flows. See Section 3.7 for more details

The proportion of consents without maximum annual volumes and without maximum instantaneous rates was calculated. For consents with maximum annual volumes and maximum instantaneous rates, summary results were given showing the median, mean and count for each category. Results were tabulated for the whole country and by source and use.

All consents were associated with grid location co-ordinates, except 15 of 1680 active consents in the Otago region. These 15 consents and their contribution to accumulated flows could not be displayed on any maps. For each map all keys and panels were ordered alphabetically. Symbols were plotted in a randomised order to avoid an overplotting bias when many points are located in close proximity. To avoid overplotting bias and to aid interpretation of results, we categorised rivers based on Strahler stream order where Small was stream orders 1 to 3, Medium was stream orders 4 and 5, and Large was stream orders 6 to 8.

3.7 Displaying the results within an interactive app

Results were also displayed using an interactive app made available to the Ministry for the Environment (Figure 3-2). For more information about this app please contact the Ministry for the Environment (info@mfe.govt.nz). This interactive app contained the following components:

- Left panel displays user choices and selected take information.
  - Region drop down menu: for changing region viewed.
  - Catchment drop down menu: to select a catchment of interest (catchment names are the names of water bodies flowing to the sea).
  - Abstractions check box: select to view locations of abstractions.
  - Hydropower check box: select to view locations and connectivity of hydropower.
  - River lines check box: select to view representation of river locations for the selected catchment.
  - Source or use selection: select colour scheme to display types of consent.
  - Influence of selection: choice of whether to show downstream influence of abstractions of hydropower (depending on whether these are present in the catchment on interest).
  - Consented rate selection: choice of analysis variable, either instantaneous rates of annual volumes.
  - Pressure type selection: choice of which type of information to plot onto river segments. None = nothing plotted. Local = cumulated downstream pressure plotted. Max. downstream = the maximum pressure found downstream of each river segment is plotted.
  - Selected Consent menu: choice of selected consent.
  - Consent information box: displays information relating to the selected consent.
- Central panel displays a map.
  - Large dots represent consents. Colours by use of source.
  - Small dots represent values at river segments. Coloured by pressure.
  - Black circles represent consumptive hydropower infrastructure.
  - White circles represent non-consumptive hydropower infrastructure.
  - Yellow circle represents the selected consent.
  - Black circle represents the selected river segment.
  - Red circle represents the river segment under most pressure downstream of the selected river segment.
- Right panel displays two barplots.

- Left barplot shows consented rates for all consents upstream of the selected river segment. Pressure, estimated median flow and segment identifier for the selected river reach are also shown.
- Right barplot shows consented rates for all consents upstream of the most pressured river segment that is downstream of the selected river segment. Pressure, estimated median flow, and segment identifier for the most pressured downstream river reach are also shown. Click on this barplot to select an influencing take.

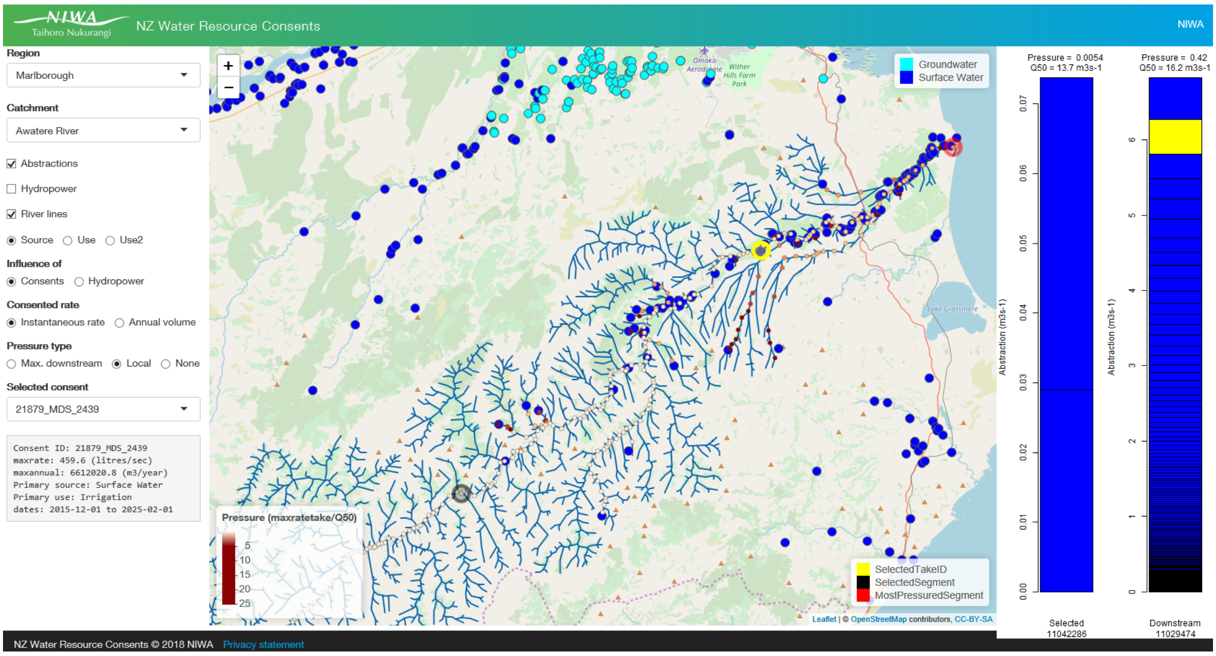

Figure 3-2: Screen capture showing the water consents interactive app.

4 Results

4.1 Summaries by use and source; non-hydropower

Quantifying patterns in numbers and size of consents by use gives an indication of what abstracted water is being used for. Quantifying patterns by source gives an indication of whether groundwater or surface water is being abstracted. Quantifying patterns by region gives an indication of regional patterns in water use.

Table 4-1 shows summary statistics nationally, by use, by source, and by region. Figure 4-1 provides a graphical summary of a subset of this information. Some findings of these results include:

- only small proportions of consents had missing values for both maxrate and maxannual;
- several consents had missing values for either maxrate or maxannual, but these values missing were replaced with modelled values;
- some consents had zero values for both maxrate and maxannual, these were mostly for stock water in the Waikato region;
- industrial uses had the highest mean maxrates, due to a few large takes for this use;
- the sum of maxrates for industrial and drinking uses was relatively low because there were relatively few consents for these uses;
- the mean and median maxrate for irrigation uses was similar to other uses (such as drinking);
- the sum of irrigation was by far the greatest of any use (excluding hydro) due to the high number of consents for this use;
- there were approximately twice as many groundwater consents than surface water consents;
- there were large differences in number of consents and quantity of allocation between regions;
- total groundwater rates were less than total surface water rates;
- there were differences in the ratios of maxrate to maxannual between sources and between uses; and
- many maxannual values equated to the volume taken over a year if maxrate was exercised constantly, but some maxannual values equate to less volume than could be taken over a year at maxrate.

Table 4-1: Summary statistics for consumptive non-hydropower consents by use, source and region. Real = maxrate and maxannual were non-zero and non-missing after having filled gaps with modelled data. Missing = both maxrate and maxannual missing. Zeros = both maxrate and maxannual zero. N Modelled = modelled values were used. Medians and means are calculated for non-zero values only.

	Number of consents				Maximum instantaneous rate ($l\ s^{-1}$)				Maximum annual volume (million m^3)			
	Total	Real	Missing	Zeros	n Modelled	Median	Mean	Sum	n Modelled	Median	Mean	Sum
National	19679	16713	166	2800	2241	11.1	58.6	979,015	802	0.08	0.77	12935.02
Use												
Drinking	1509	1426	22	61	196	5.4	65.0	92,755	170	0.09	1.52	2164.90
Hydroelectric	44	0	10	34	NA	NA	NA	NA	NA	NA	NA	NA
Industrial	1146	957	33	156	178	8.3	106.9	102,345	98	0.13	1.35	1296.63
Irrigation	11249	11116	34	99	1369	15.0	57.4	638,252	370	0.12	0.67	7450.64
Other	5731	3214	67	2450	498	3.2	45.3	145,663	164	0.03	0.63	2022.86
Source												
Groundwater	13659	11573	60	2026	1814	8.2	25.3	292,286	43	0.06	0.27	3104.27
Surface Water	6020	5140	106	774	427	20.6	133.6	686,729	759	0.22	1.91	9830.75
Region												
Northland	491	471	0	20	7	1.4	10.6	4,985	0	0.02	0.52	245.03
Auckland	861	845	9	7	819	4.5	17.2	14,568	1	0.01	0.10	86.96
Waikato	2724	766	0	1958	399	5.8	117.1	89,718	115	0.03	1.00	764.22
Bay of Plenty	109	109	0	0	0	16.7	28.5	3,102	0	0.06	0.13	13.70
Gisborne	161	160	0	1	1	8.0	22.1	3,528	0	0.07	0.29	46.36
Taranaki	183	183	0	0	7	15.0	38.1	6,979	0	0.18	1.02	185.90
Manawatu- Wanganui	1544	988	0	556	0	2.7	22.0	21,731	0	0.06	0.53	523.87
Hawke's Bay	2768	2585	0	183	4	18.9	31.4	81,081	10	0.07	0.23	587.09
Greater Wellington	478	450	28	0	1	15.8	55.8	25,122	17	0.17	1.12	503.59
Tasman	835	835	0	0	0	2.9	7.7	6,429	0	0.03	0.09	72.73
Marlborough	1444	1398	46	0	925	7.0	24.8	34,636	7	0.06	0.37	518.21
West Coast	225	154	0	71	31	19.0	67.1	10,334	0	0.34	1.88	290.25
Canterbury	5228	5227	0	1	9	20.0	99.4	519,382	105	0.23	1.17	6116.08
Otago	1765	1680	83	2	8	27.8	85.8	144,143	547	0.40	1.65	2772.86
Southland	863	862	0	1	30	1.2	15.4	13,276	0	0.03	0.24	208.17

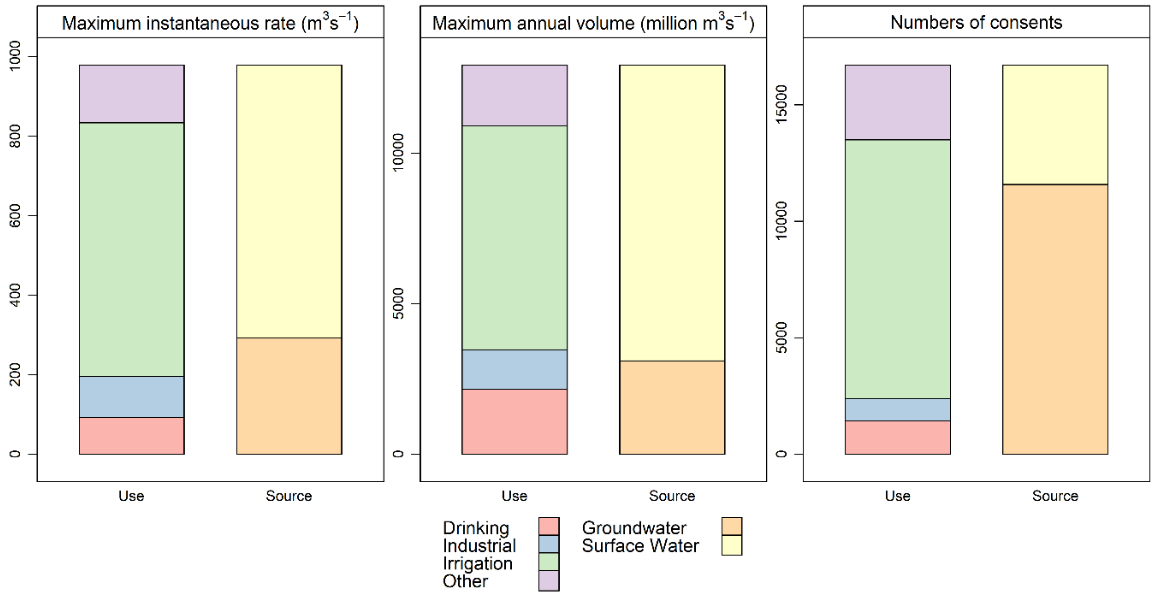

Figure 4-1: Summary information for non-hydropower consents. Number of consents refers to consents where either maxrate or maxannual were non-zero and non-missing.

4.2 Accumulated consents; non-hydropower

The total upstream accumulated maximum take (AccMaxrate) of each segment in the New Zealand national digital river network standardised by naturalised median flow was calculated. This is a useful indicator of pressure on stream flows because it reflects the likely proportional reduction in flow that would result from maximum consented use regardless of restrictions.

Maps of the standardised AccMaxrate for consumptive non-hydropower consents show the highest pressure on flow regimes is likely to occur in smaller rivers, where proportionally more water is consented (Figure 4-2). The disbursed pattern of surface water takes often results in high standardised AccMaxrates in the headwaters of smaller streams, which then often reduce with distance downstream because of increases in the median flow. For example, high pressure in small and medium sized rivers and streams in Central Otago. In contrast, the concentrated pattern in groundwater takes in lowland areas often result in high standardised AccMaxrates across specific catchments. This is particularly the case across the Canterbury Plains, coastal areas of Hawke's Bay and in lowland catchments in the Horizons region.

Maps of accumulated standardised AccMaxrate gave further evidence that irrigation uses resulted in the highest rates of stream depletion across the country, although takes for industrial and drinking uses are important in some catchments (Figure 4-3).

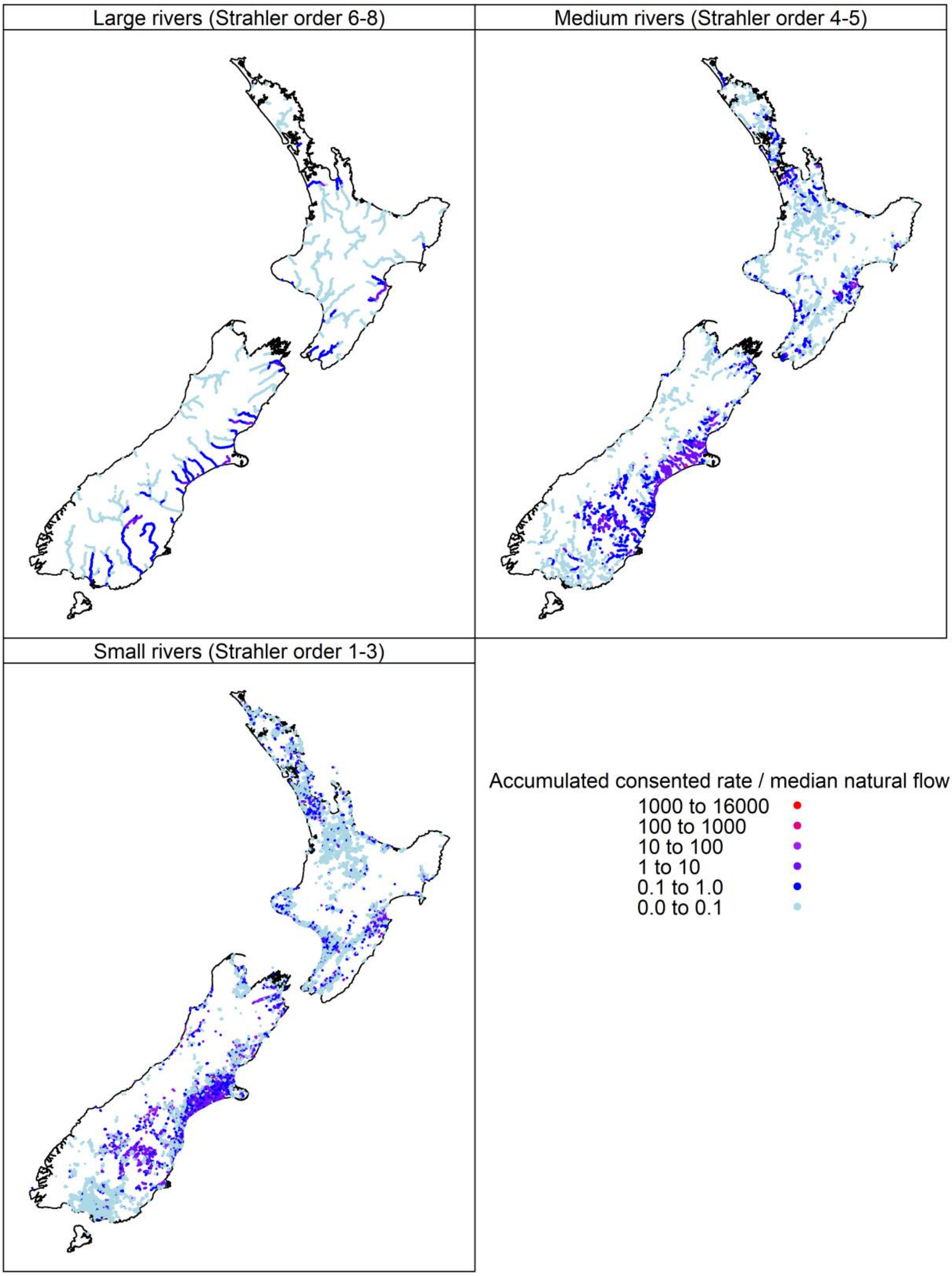

Figure 4-2: Map of accumulated upstream consented takes relative to median flow (standardised AccMaxrate) by river size for consumptive non-hydropower consents.

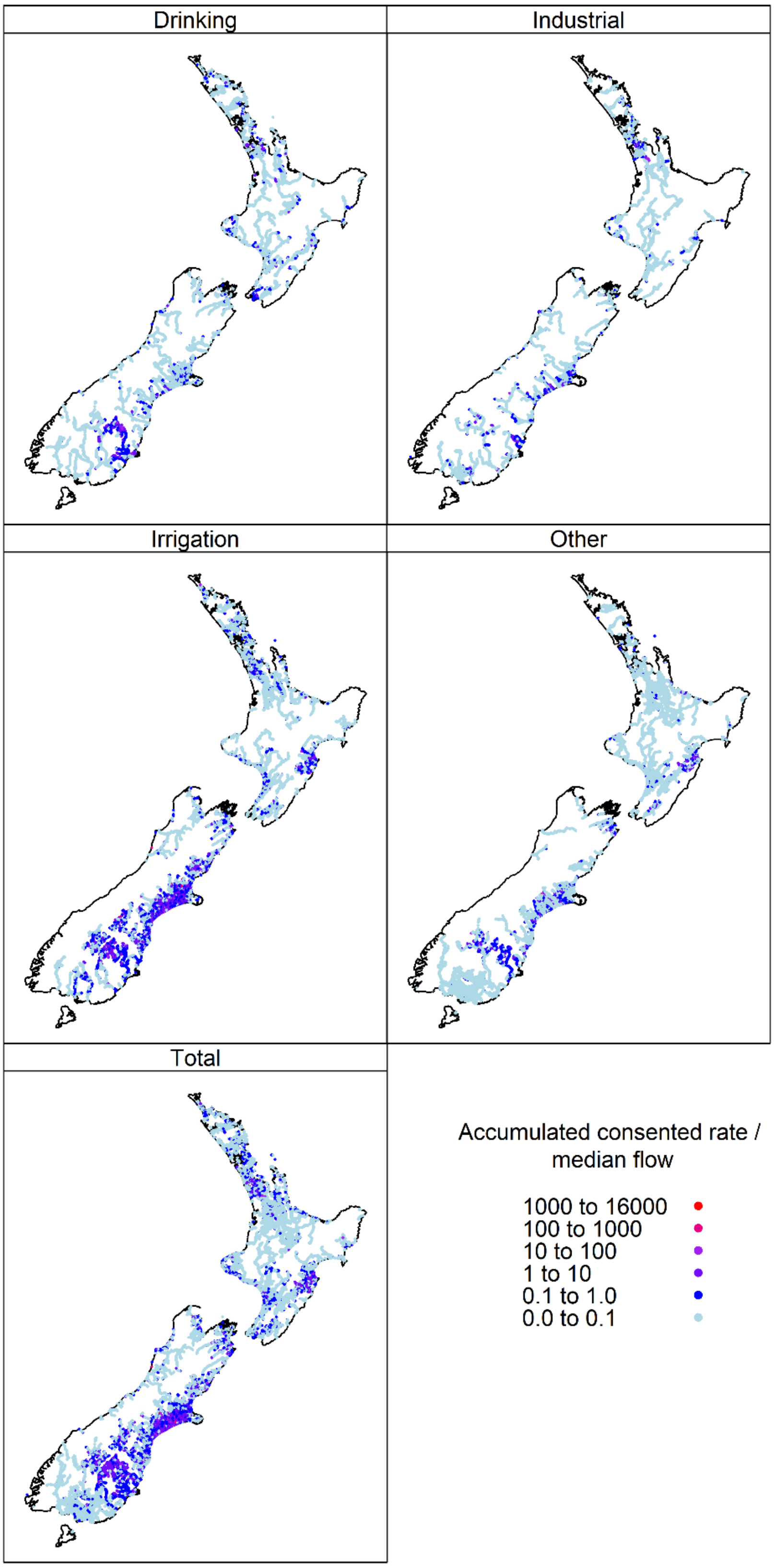

Figure 4-3: Map of accumulated upstream consented rate of take relative to median flow (standardised AccMaxrate) by use for consumptive non-hydropower consents.

4.3 Accumulated consents; hydropower

We mapped the potential impact of consumptive hydropower consents on river flows. Results indicated that the potential influence of consumptive hydropower consents was confined to a few, mainly larger rivers (Figure 4-4). Results indicated that consumptive hydropower uses have the potential to greatly deplete some large rivers (e.g., the Southland Waiau). In some cases, inter-basin transfers schemes augmented flows in one river (e.g., Waikato River) whilst simultaneously depleting flows in others (e.g., Whanganui River, Whangaehu River). In cases where transfers were contained within a catchment, a length of river was depleted, but this depletion was balanced by augmentation a point before the river reached the sea (e.g., Manawatu River).

In some locations abstraction from non-hydropower consents exceeded flow augmentation from hydropower consents, resulting in net positive pressure (flow depletion) at some point downstream of the hydropower operations (e.g., Lower Rakaia). In other locations abstractions from non-hydropower consents did not exceeded flow augmentation from hydropower consents, resulting in net negative pressure (flow augmentation) at all locations downstream of the hydropower operations (e.g., Waikato River; Figure 4-4).

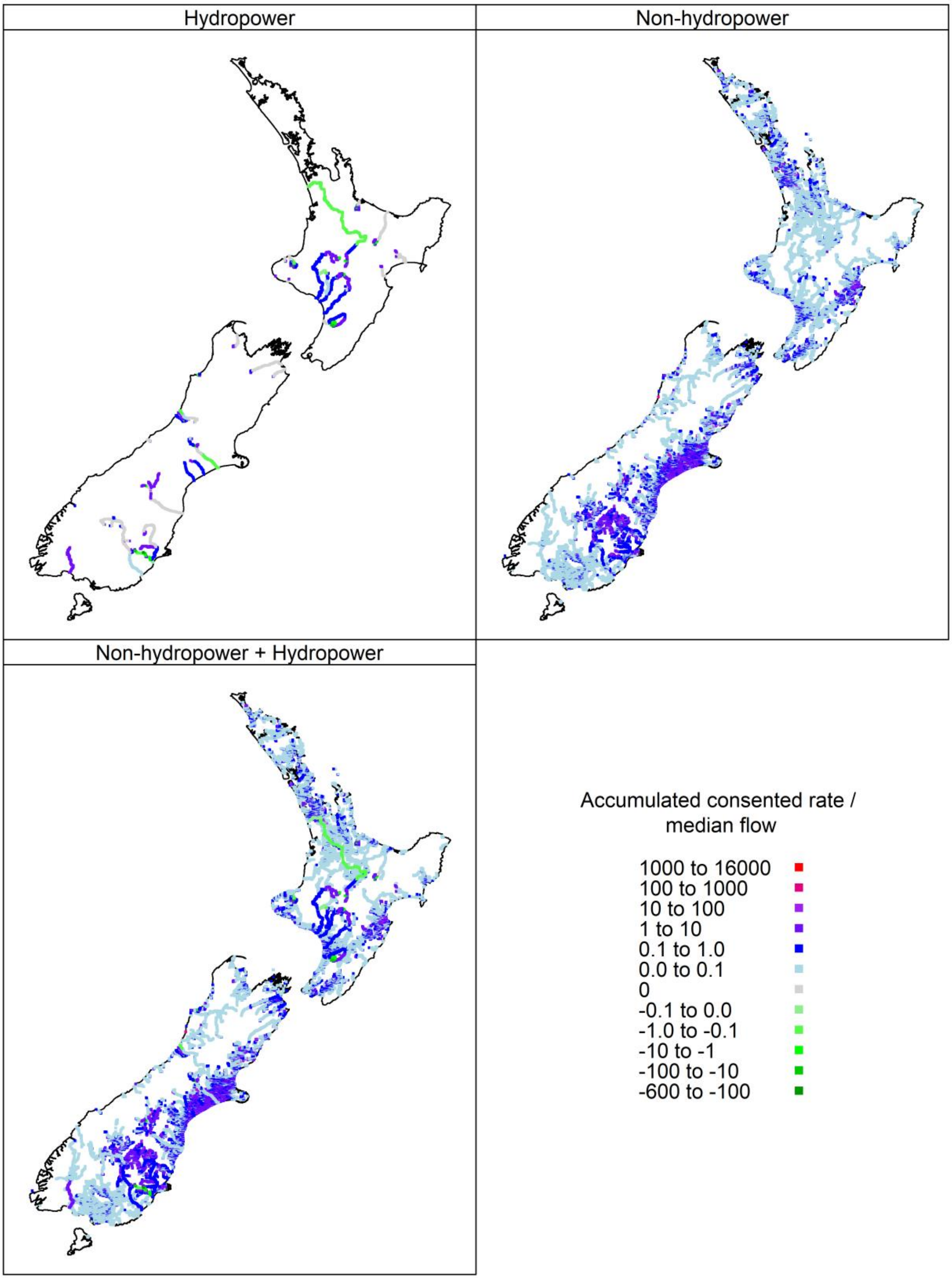

Figure 4-4: Map of accumulated upstream consented takes relative to median flow (standardised AccMaxrate) for consumptive consents for hydropower, non-hydropower, and their total.

5 Discussion

5.1 River flow depletion from groundwater

Data describing the depths of groundwater bores, or the connectivity of groundwater to surface water (e.g., where groundwater was being taken from a confined aquifer) were not available for all groundwater abstractions. We therefore assumed that all groundwater takes would result in some level of streamflow depletion. This was the same method applied by Booker et al. (2016) and can be viewed as a worst-case scenario for impacts on river flows.

5.2 Regional variations in provided data

Results indicate regional variations in the type of activities that require consents or the type of consents that were included in the supplied datasets. This was particularly the case for stock water and hydropower consents. Many consents for stock water uses were included in the supplied datasets from the Southland, Waikato and Horizons regions. In contrast, very few consents for stock water were included in the remaining regions. Aside from including stock water consents in our analysis, we did not attempt to estimate the influence of water taken for stock water as a permitted activity.

The number of consents that we obtained information for, but which had passed their expiry date varied by region (Table 3-1). Large numbers of expired consents from the Auckland, Horizons, Hawke's Bay, Greater Wellington and Tasman regions indicated that the available data from these regions might be suitable for an historical analysis of changes in consents through time. However, a lack of historical consent information for other regions (e.g., Canterbury and Otago) indicated that an historical analysis would not be possible using the available data from these regions.

5.3 Hydropower schemes

Some hydropower schemes (e.g., Manapouri) were included in the supplied datasets. We used those data to help create a separate dataset describing consumptive hydropower consents and infrastructure. We added known information on consents for large consumptive hydropower schemes when these schemes were not included in the supplied datasets. This included the Waikato dams and Tongariro Power Development scheme that were not supplied. We did not include non-consumptive hydropower schemes in this analysis because those schemes do not deplete river flows over the long-term. However, non-consumptive hydropower schemes do have the ability to greatly alter river flows in the short-term mainly through storage in reservoirs followed by release at a later time. Methods for quantifying hydrological alteration caused by hydropower schemes, along with examples are provided by Griffiths and Booker (2019). We displayed the location of known non-consumptive hydropower schemes in our app.

5.4 Restrictions

Consents to abstract water can include the enforcement of restrictions (i.e., where abstractions cease or are reduced due to low river flow, low groundwater levels or other specified conditions). Enforcement of restrictions are designed to reduce stream depletion in situations where demand to take water is large compared with supply. No data describing restriction of consents were available for this dataset. When accumulating we therefore assumed a worst-case scenario where all consents are unrestricted.

5.5 Data curiosities

Generally, we assumed that the supplied data were accurate and fit for the purposes of national environmental reporting. However, we also applied our own quality checks. These included comparisons between maximum instantaneous rate and maximum annual volume.

We noticed some curious features within the dataset whilst conducting our analysis. These included:

- Many consents where maxannual was zero and maxrate was either zero or missing.
- For some consents maxannual was greater than maxrate multiplied by the number of seconds in a year. We did not change either value in this case, as it was unknown which value was incorrect.
- Some consents with very large maxrate and maxannual values that were most likely not intended for on-going consumptive use. For example, a consent for industrial use at the outflow point of Lake Waikare on a tributary to the Waikato river with an estimated median flow of 2 m^3s^{-1} for a maxrate of 53 m^3s^{-1}.

5.6 Is this analysis comparable with previous analyses?

The aim of this work was to obtain the truest possible representation of water allocation across New Zealand. Our aim was not to allow a comparison between 2018 and previous estimates of water allocation. Whilst we endeavoured to maintain consistency with the method previously applied by Booker et al. (2016) to calculate maxrate and maxannual, there are several reasons why results from the present analysis cannot be directly compared with those from the previous analysis.

- The upstream accumulation analysis was carried out on version 2 rather than version 1 of the national digital river network as used for the Booker et al. (2016) report. It should be noted that nzsegments from version 2 are not directly comparable with NZReaches from version 1 of the national digital river network.
- More rigorous data checks were applied prior to the present analysis in comparison to those applied for the Booker et al. (2016) report. These checks resulted in the removal of some consents that had been entered twice and some consents whose maximum consented rate was entered in the wrong units (e.g., a groundwater take for the purposes of stock water drinking with unfeasibly large instantaneous maximum allowable rate compared with its annual volume).
- We undertook a more rigorous inspection of consent use with respect to “hydropower” versus other uses for this report in comparison with that applied in the Booker et al. (2016) report. We relabelled some “irrigation” uses to be “hydropower” and some “hydropower” uses to be “irrigation” based on inspection of the consent data, inspection of aerial photography, and our understanding of the main purpose of the schemes. It should be noted that labelling of consent use can be very influential when summing across non-hydropower consents since hydropower uses tend to be for very large volumes or rates. Furthermore, there can be ambiguity between hydropower and other uses within a consent. This often comes about when water used for hydro-electric generation is then passed on to be used for irrigation or other purposes (e.g., Opuha Dam, Rangitata Diversion Race, etc.).

- We applied the same methods to tabulate maxrate and maxannual as were applied for the 2016 report. We note that regression models were used to infill NA (missing) maxAnnual values. A separate regression model was fitted and then applied for maxrate and maxannual on each occasion. The 2016 missing data were infilled using models fitted to the 2016 data. The 2018 missing data were infilled using models fitted to the 2018 data. The 2016 and 2018 regression models took the same formulation. Maxannual was predicted from maxrate, source, use and region. Maxrate was predicted from maxannual, source, use and region. Any changes in source, use, region, and either maxrate or maxannual within the data available for the 2016 and 2018 analyses will be reflected in the models applied to fill NA values.
- A naïve comparison would show an apparent increase in total annual volume of consented water between 2016 and 2018 of 3,061 Mm^3. This is equivalent to a 31% increase. However, inspection of the data obtained in 2016 and 2018 demonstrated that regional councils have changed their procedures for uploading of consents and/or their interpretation of which consents qualify as being for consumptive water use (Table 5-1).
  - 24% more consents were obtained in 2018 compared to 2016.
  - Fewer consents had missing maxAnnual and maxRate in 2018 compared to 2016.
  - 5,360 consentID’s appeared in the 2018 analysis that did not appear in the 2016 analysis. Of these 5,360 consents, 3,994 had commencement dates before February 2016. This indicates that many consents supplied for the 2018 analysis were active in 2016 but were not incorporated into the 2016 analysis. The sum of the consents provided for 2018 but commencing prior to 2016 was 4,480 Mm^3. This is more than the 3,061 Mm^3 difference in calculated total annual volumes for 2016 and 2018.
  - Many more consents were supplied for the 2018 analysis compared to the 2016 analysis for the Northland, Hawke’s Bay, Canterbury and Otago regions. This resulted in greater summed maxrate and maxannual in these regions for 2018 compared to 2016. For all four of these regions most of the newly supplied consents commenced before 2016.
  - Many more consents were supplied for the 2018 analysis compared to the 2018 analysis for the Waikato region, but this did not result in greater summed maxAnnual for that region. This was because for 2018 Waikato Regional Council supplied around 2,000 extra consents with missing or zero maxAnnual and maxrate. Further inspection of consent details revealed that most of these consents represent stock drinking for permitted activities.
  - There was a large increase in maxAnnual but a very small change in number of consents between 2016 and 2018 for Gisborne. Inspection of the data suggests a change in units of the data supplied by Gisborne District Council between 2016 and 2018. Verification of the supplied data against information on GDC website suggested that maxannual supplied in 2016 incorrectly took units of maximum daily volume (m^3/day), and therefore should have been multiplied by 365.

Fortunately, a very small proportion of the national consented volume is in the Gisborne region.

- The above analysis suggests (but does not definitively prove) that most of the increase in total maxAnnual between 2016 and 2018 can be attributed to an increase in our knowledge of the present consents stemming from improved data availability rather than a real rise in consented volume between 2016 and 2018. Unfortunately, this is challenging because:
  - To the best of our knowledge not all regional councils are maintaining historic consents conditions as part of their data delivery services. For example, councils may be removing old consents or overwriting old consent conditions from their data services as consent details are updated. These practices are logical if snap-shots of water allocation are required. These practices are not conducive for calculating reliable time-series of consented water allocation.
  - New consents can be granted to replace old consents even before the older consent expires.
  - More information than just commencement and expiry dates are required for a complete and reliable time-series analysis of consented water allocation because of complications such as consent transfers and RMA S124 continuances etc.
- We would recommend that any time-series analysis of national or regional maxrate or maxannual must be carried out using a single dataset containing all available information on all active and expired consents.

Table 5-1: Number of consents in each region.

Region	Total maxAnnual (million m^3)			Number of consents (including zero and missing)			Number of non-missing non-zero consents		
	2016	2018	Difference	2016	2018	Difference	2016	2018	Difference
Northland	19.03	245.03	226.01	350	491	141	350	471	121
Auckland	93.73	86.96	-6.77	936	861	-75	918	845	-73
Waikato	1,209.73	764.22	-445.51	990	2724	1734	790	766	-24
Bay of Plenty	11.91	13.70	1.78	86	109	23	86	109	23
Gisborne	0.21	46.36	46.14	145	161	16	145	160	15
Taranaki	178.70	185.90	7.21	166	183	17	166	183	17
Horizons	1,100.75	523.87	-576.88	905	1544	639	868	988	120
Hawkes Bay	347.63	587.09	239.46	2094	2768	674	1951	2585	634
Wellington	631.69	503.59	-128.10	542	478	-64	511	450	-61
Tasman	90.90	72.73	-18.17	981	835	-146	981	835	-146
Marlborough	551.29	518.21	-33.08	1361	1444	83	1346	1398	52
West Coast	238.03	290.25	52.21	170	225	55	142	154	12
Canterbury	4,168.44	6,116.08	1,947.65	4771	5228	457	4771	5227	456
Otago	996.74	2,772.86	1,776.12	1482	1765	283	915	1680	765
Southland	235.58	208.17	-27.41	942	863	-79	940	862	-78
National	9,874.35	12,935.02	3,060.66	15,921	19,679	3,758	14,880	16,713	1,833

6 Conclusions

The analysis provided in this report can be used to represent several indicators of water allocation and pressure on river flows. The analysis is nationally consistent because the same methods were applied universally across the country. The results provide defensible indicators of nationwide patterns in water allocation, including where water has been consented, what water is being used for, and the likely influence of unrestricted consented water abstraction on river flows.

7 Acknowledgements

Many thanks to James King of MfE for discussion and assistance in providing data. Many thanks to various regional council staff for assistance in providing data.

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